PB87-179255

Multistaged Approach for In-Furnace NOx Control

Acurex Corp., Research Triangle Park, NC

Prepared for

Environmental Protection Agency
Research Trianle Park, NC

Apr 87

U.S. Department of Commerce
National Technical Information Service
NTIS

PB87-179255

EPA/600/D-87/116
April 1987

A MULTISTAGED APPROACH FOR IN-FURNACE NO_X CONTROL

by

R. K. Srivastava
Acurex Corporation
Durham, NC 27713

J. A. Mulholland
Air and Energy Engineering Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

EPA Contract 68-02-3988

EPA Project Officer
James A. Mulholland

AIR AND ENERGY ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA/600/D-87/116		

4. TITLE AND SUBTITLE	5. REPORT DATE
A Multistaged Approach for In-Furnace NO_x Control	April 1987
	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
R. K. Srivastava (Acurex) and J. A. Mulholland (EPA/AEERL)	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Acurex Corporation Durham, North Carolina 27713	11. CONTRACT/GRANT NO. 68-02-3988

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
EPA, Office of Research and Development Air and Energy Engineering Research Laboratory Research Triangle Park, NC 27711	Published paper; 8/86 - 2/87 14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES AEERL project officer is James A. Mulholland, Mail Drop 65, 919/541-7663.

16. ABSTRACT The paper discusses the evaluation of a multistaged combustion burner design on a 0.6 MW package boiler simulator for in-furnace NOx control and high combustion efficiency. The adiabatic precombustion chamber burner has been reduced in size by a factor of about 2. Natural gas, doped with ammonia to yield a 5.8% fuel nitrogen content, was used to simulate high nitrogen content fuel/waste mixtures. A burner baseline NO emission of 315 ppm (measured dry, corrected to zero % O2) was measured, compared with an emission of over 1000 ppm estimated for a conventional unstaged burner. Both deep air staging, resulting in a three-stage configuration, and boiler front wall fuel staging of undoped natural gas, yielding four stoichiometric zones, reduced the baseline NO emission by about 50% to 160 ppm, meeting the program goal. However, deep air staging resulted in the entire front end of the boiler being fuel-rich and required penetrations into the boiler for staged air injection. The fuel staging results, on the other hand, required no boiler penetrations and only a small fuel-rich flame core in the boiler. Further, sufficient air for complete oxidation of the primary combustion products was provided at the burner exit, prior to staged fuel and air injection in the boiler, in the fuel staging tests.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Burners	Stationary Sources	13A
Nitrogen Oxides	Multistaged Burners	07B
Combustion Efficiency		21B
Fossil Fuels		21D

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to Public	Unclassified	27
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

A Multistaged Approach for In-Furnace NO_x Control

R.K. Srivastava* and J.A. Mulholland**

U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory

ABSTRACT

A multistaged combustion burner design is being evaluated on a 0.6 MW package boiler simulator for in-furnace NO_x control and high combustion efficiency. An adiabatic precombustion chamber burner has been reduced in size by approximately a factor of two. Natural gas, doped with ammonia to yield a 5.8 percent fuel nitrogen content, was used to simulate high nitrogen content fuel/waste mixtures. A burner baseline NO emission of 315 ppm (measured dry, corrected to zero percent O_2) was measured, compared with an emission of over 1000 ppm estimated for a conventional, unstaged burner. Both deep air staging, resulting in a three-stage configuration, and boiler front wall fuel staging of undoped natural gas, yielding four stoichiometric zones, reduced the baseline NO emission by about 50 percent to 160 ppm, meeting the program goal. However, deep air staging resulted in the entire front end of the boiler being fuel-rich and required penetrations into the boiler for staged air injection. The fuel staging results, on the other hand, required no boiler penetrations and only a

---

* Mechanical Engineer, Acurex Corporation, Durham, NC 27713.
** Mechanical Engineer, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711.

small fuel-rich flame core in the boiler. Further, sufficient air for complete oxidation of the primary combustion products was provided at the burner exit, prior to staged fuel and air injection in the boiler, in the fuel staging tests. Thus, a four-stage configuration appears to be the most promising approach for minimizing NO emissions and maximizing primary fuel/waste destruction. Further testing is ongoing with pyridine and fuel oil mixtures to better characterize surrogate fuel/waste destruction efficiency.

INTRODUCTION

The family of nitrogen oxide compounds, including nitric oxide (NO) and nitrogen dioxide (NO_2), is generally referred to as "NO_x." These NO_x are formed during the combustion of coal, oil, and natural gas by the reduction and oxidation of molecular nitrogen (N_2) and nitrogen contained in the fuel. NO_2 is a poisonous gas that the United States Environmental Protection Agency (EPA) has designated as a criteria pollutant because of its human health effects [1,2]. Further, NO_x are known to contribute to the formation of photochemical oxidants and are precursors, along with sulfur oxides (SO_x), of acid precipitation. Two more areas of concern are emerging in regard to NO_x levels in the atmosphere. First, forest damage, reported to be extensive in the Federal Republic of Germany [3], has been linked with increasing NO_x levels. Second, increasing levels of atmospheric nitrous oxide (N_2O) have been measured, levels that have been predicted to contribute to both a decline in the abundance of stratospheric ozone and an increase in climatic warming [4]. Studies of N_2O and NO concentrations in experimental flames and in flue gases have shown that a strong correlation exists between these two gases formed in combustion processes.

The EPA estimates that about 20 million tons (18,000 Gg) of NO_x are emitted annually from stationary and mobile sources in the United States. Unlike SO_x emissions, NO_x emissions have been increasing [5]. Coal- and oil-fired

utility and industrial boilers account for over half of these NO_x emissions. Only 15 percent of these stationary sources are regulated by EPA's New Source Performance Standards (NSPS) [6]; the remainder must be addressed with retrofit technologies if significant NO_x emission reduction is to be realized. Another NO_x control problem is posed by the potential of incinerating high nitrogen content wastes in industrial boilers. While incineration of these materials would not constitute a significant increase in the overall national NO_x emission level, individual plant emissions may be sufficient to result in a local NO_x problem and, thus, prevent on-site incineration from being permitted. With thermal destruction being an attractive alternative to landfill storage of wastes, there continues to be a need for developing high efficiency, low NO_x combustion technologies.

By far, the major portion of NO_x have been found to be NO. Much is known about the mechanisms of NO formation in flames, both from molecular nitrogen (source of thermal NO) and from fuel-bound nitrogen (source of fuel NO). Thermal NO can be reduced by decreasing peak flame temperatures. Fuel NO, not as strongly dependent on temperature, is very sensitive to reactant stoichiometry. Fuel-rich conditions promote N_2 formation over NO formation. Laboratory studies and field test data have established the importance of fuel NO to the total emission of NO_x from residual fuel oil and coal flames. Therefore, minimizing NO_x formation in flames typically involves controlling air and fuel mixing rates to create fuel-rich reducing zones and extracting heat to reduce final oxidation temperatures.

To avoid the need for costly post-combustion NO_x removal, several in-furnace NO_x control strategies have been developed and applied to boilers. These include reduced air preheat, load reduction, low excess air, flue gas recirculation, overfire air, deep air staging, fuel staging (or reburning), and various low-NO_x

burner systems [7]. While NO_x emissions can be reduced by 20 to 80 percent using these technologies, from uncontrolled levels exceeding 1000 ppm for some high nitrogen content coals, application of these combustion modifications can result in reductions in combustion efficiency and increases in sooting and slagging in the boiler. This problem is of particular concern in the boiler co-firing of fuels and wastes, where high waste destruction efficiencies and minimal formation of other incomplete combustion products are of paramount importance. The purpose of this work is to investigate various multistaged combustion concepts for burning high nitrogen fuel/waste streams with low NO_x emissions and high combustion efficiency. Specifically, tests were designed to evaluate the use of an adiabatic precombustion chamber burner, modified to reduce burner size, coupled with air or air/fuel staging. A NO_x emission of less than 0.2 lb (as NO_2)/10^6 Btu* (or approximately 175 ppm NO_x, measured dry at zero percent O_2) for firing gaseous and liquid fuels doped with up to 5 percent nitrogen (by weight) was targetted. The study is ongoing; in this paper pilot-scale test results are presented on the NO_x emission performances of the proposed firing designs. Future work will evaluate the combustion efficiency performances.

Before describing the experimental procedure and results, some background information is provided.

Adiabatic Precombustion Chamber Burner

The adiabatic precombustion chamber burner is a staged combustion technology capable of achieving a NO_x emission of less than 0.1 lb (as NO_2)/10^6 Btu (or approximately 90 ppm NO_x), even with high nitrogen fuel firing [8]. It consists of a primary air and fuel injection system, a large refractory wall precombustion chamber, and a secondary air injection section. Fuel and primary

* The current NSPS for large industrial boilers firing high nitrogen heavy fuel oil is 0.4 lb/10^6 Btu. This standard is under review. (1 lb/10^6 Btu = 0.43 kg/GJ.)

air are injected for rapid mixing into the nearly adiabatic precombustion chamber with a first-stage stoichiometry of between 0.6 and 0.8.* A residence time between 0.6 and 1.0 s allows for maximum reduction and conversion of fuel nitrogen species to N_2 in the fuel-rich precombustion chamber. First-stage combustion gas products exit the burner through a convergent section which minimizes both radiative heat loss to the boiler and back-mixing of the secondary air. The transition section between the burner and boiler is water-cooled to reduce combustion gas temperatures before final air addition.

The precombustion chamber burner has been tested on a full-scale (16 MW_t) crude oil-fired steam generator used for thermally enhanced oil recovery (TEOR) in Kern County, CA [9]. A 30-day continuous monitoring test demonstrated the burner's ability to maintain a nominal NO emission of 70 ppm with a high combustion efficiency [10]. During burner optimization testing, NO, CO, and smoke emissions were measured over a range of first-stage stoichiometries. These data indicate the sensitivity of NO emission to first-stage stoichiometry and the good hydrocarbon burnout characteristics of the burner. Earlier pilot-scale tests firing nitrogen-free fuels suggest that the minimum NO_x level of about 50 ppm can be attributed to second-stage thermal NO formation.

A test designed to demonstrate the potential for using this burner for nitrogenous waste incineration was performed at EPA's Air and Energy Engineering Research Laboratory. A pilot-scale (0.6 MW) precombustion chamber burner was used to incinerate a surrogate nitrogenous waste mixture of 9.1 percent (by volume) pyridine in fuel oil. A NO emission of less than 100 ppm was maintained, with greater than six nines (99.9999 percent) destruction of the pyridine being

---

* The stoichiometric ratio (SR), the actual air-to-fuel ratio divided by the theoretical air-to-fuel ratio, is used throughout this paper.

achieved. The relative NO emissions with and without pyridine addition indicate that less than 1 percent of the fuel nitrogen was converted to NO. This preliminary result sparked interest in utilizing the precombustion chamber burner for high efficiency, low NO_x combustion.

However, while the precombustion chamber burner has been demonstrated successfully in pilot-scale and field tests, its large size makes it impractical for most boiler retrofit applications. Reducing the burner size results in insufficient first-stage residence time to fully convert the fuel nitrogen to N_2; hence, higher NO emissions result. Further NO_x control can be achieved by further staging of the combustion process in the boiler.

Staged Combustion

The concept of staged combustion consists of injecting secondary air into the boiler downstream of the primary combustion zone, which is characterized by substoichiometric levels of combustion air. This concept may be employed by utilizing overfire air ports, secondary air injectors, or burners-out-of-service. In application with a shortened precombustion chamber burner, further air staging would extend the fuel-rich first stage from the burner into the boiler.

Reburning

As many as 30 years ago, experimental results were available indicating that NO could be destroyed by reaction with hydrocarbon radicals. Early fundamental studies of NO destruction by injection of secondary fuel into the flame zone were performed by Wendt et al. [11], who coined the name "reburning" to describe the process. Concerted effort to develop reburning for application to boilers occurred in Japan during the late 1970's and early 1980's. The first reporting of these efforts was by Takahashi et at. [12], documenting extensive laboratory-, pilot-, and full-scale evaluations of a fuel staging process they refer to as Mitsubishi Advanced Control Technology, or MACT.

Since 1982 EPA has carried out both in-house and extramural bench- and pilot-scale reburning tests. In-house experiments have focussed on natural gas and fuel oil reburning [13-16]. Significant findings include defining the dependence of reburning effectiveness on primary flame NO level, reburn zone stoichiometry, and reburn fuel nitrogen content. Fifty percent NO reduction is possible with 10 to 20 percent of the fuel used for reburning. At low primary NO levels, however, a nitrogen-free reburning fuel (such as natural gas) must be used to achieve 50 percent reduction. Tests have shown that reburning is effective over a wide range of temperatures and with relatively short reburning zone residence times (0.2 to 0.4 s).

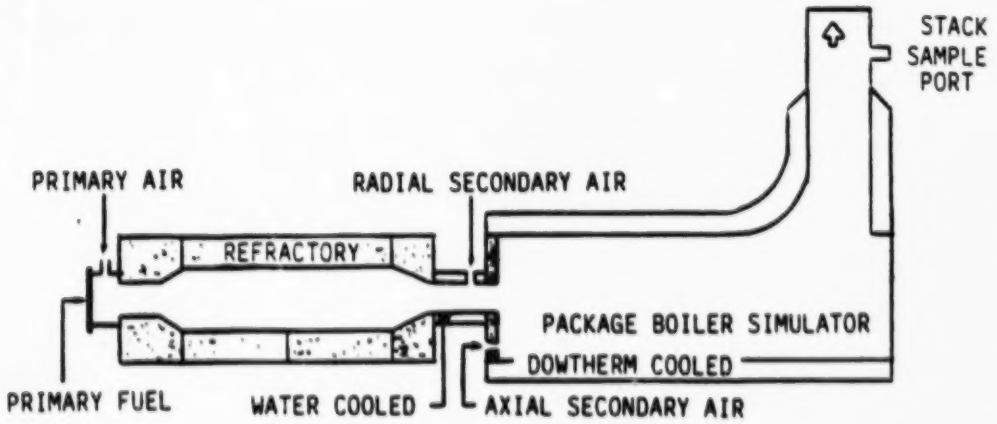
In application with a shortened precombustion chamber burner, reburning would result in a four-stage combustion process. Because much of the primary fuel has been reduced prior to boiler entry, reburning might be applied from the front wall of the boiler. Such reburning application would simplify the boiler retrofit requirement by not requiring multiple boiler penetrations.

EXPERIMENTAL PROCEDURE

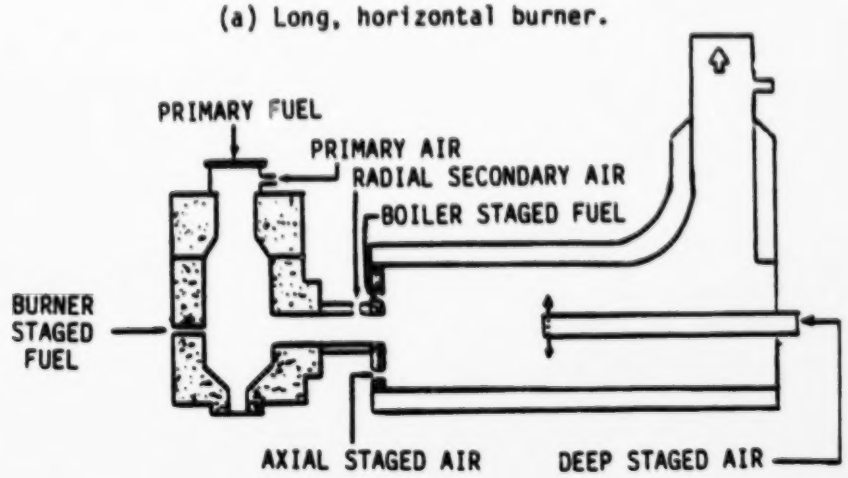
The goal of this study is to minimize NO formation, with an emission target of 175 ppm (dry, at zero percent O_2) or less, and maintain efficient incineration in the combustion of surrogate fuel/waste mixtures with up to 5 percent fuel nitrogen by using a precombustion chamber burner reduced in size by about half.

The unmodified facility, shown schematically in Figure 1a, is comprised of a precombustion chamber low-NO_x burner and a package boiler simulator. The precombustion chamber burner consists of a primary fuel and air injection module, two 0.89 m long spool modules with 0.51 m internal diameter, and a 0.33 m long convergent module. These burner modules have a thick refractory wall lining to minimize heat loss, maintaining the high temperatures that promote conversion of fuel nitrogen to N_2 under fuel-rich stoichiometries. To achieve rapid mixing in

the precombustion chamber, the primary fuel is injected through a divergent nozzle and the primary air, which is not preheated, is passed through fixed swirl vanes. The convergent module minimizes back-mixing of combustion gas and radiation loss to the boiler. A water-cooled transition module, 0.25 m in internal diameter, cools the combustion gas before secondary air addition to minimize thermal NO generation. Primary fuel nitrogen is simulated by doping ammonia into natural gas or pyridine into distillate fuel oil. All of the results



(a) Long, horizontal burner.



(b) Short, vertical burner.

Figure 1. Pilot-scale combustion research facility. The package boiler simulator has been fitted with a precombustion chamber burner and air and fuel staging ports.

reported here are with the gaseous fuel.

The pilot-scale boiler simulator is rated at 0.9 MW thermal input. The boiler's radiant section is horizontal, 0.6 m in diameter, 3.0 m long, and cooled with Dowtherm G® heat transfer fluid. Combustion gas exits the boiler through a vertical stack. The boiler's front face has eight axial ports for addition of staged air.

The research facility was modified as shown in Figure 1b. The horizontal 2.62 m long precombustion chamber burner was replaced with a shorter 1.80 m long vertical burner. This shorter burner, with a nominal residence time of 250 ms, has all the essential design features of the long horizontal burner, which has a nominal residence time of 600 ms. The elbow section has a 5 cm diameter port for staging fuel into the burner. Two of the eight axial air ports on the boiler front face were modified to provide ports for staging fuel into the boiler at an angle of 45 degrees. This design allows for reburning application from the boiler front face, with aerodynamic separation of the fuel-lean and fuel-rich zones in the boiler. The end plate of the boiler has been modified to allow the insertion of a water-cooled boom for deep staging of air into the boiler.

The experimental facility is designed for independent control and measurement of each fuel, fuel dopant, and air stream. Stack gas speciation is measured by a continuous emissions monitoring system. NO and NO_x are measured by chemiluminescence. Reported in this paper are NO measurements only, measured on a dry basis and corrected to zero percent O_2. Spot-check measurements of NO_x indicated that NO emissions accounted for over 95 percent of the exhaust NO_x emissions.

Evaluated were burner baseline performance and burner operation with various unstaged, air staged, and fuel staged NO controls. The parameters affecting the NO emissions from the facility with unstaged controls are fuel nitrogen content,

combustion gas residence time in the prechamber, first-stage stoichiometry, and exhaust stoichiometry. The residence time of combustion gas in the burner depends on precombustion chamber length, load, and stoichiometry. The nominal load was 0.6 MW. The exhaust stoichiometry was kept at a nominal value of 15 percent excess air, as per commercial boiler practice. Nominal fuel nitrogen content was chosen to be 5.8 percent by weight.

During burner baseline performance tests, the effects of burner length and first-stage stoichiometry on NO emissions were studied. Three burner configurations, two with a horizontal orientation and residence times of 600 and 350 ms and one with a vertical orientation and a residence time of 250 ms, were evaluated. With each burner configuration, the first-stage stoichiometry was varied by changing the primary and secondary air inputs.

Unstaged NO controls included excess air variation, load variation, and co-firing variation. At each test condition, first-stage stoichiometry was optimized by adjusting the appropriate air flow rates. For the co-firing tests, the ammonia dopant level in the fuel stream was varied to simulate the situation of co-firing a nitrogen-free fuel (natural gas) with surrogate waste containing 5.8 percent nitrogen.

During air staged NO control tests, the effect of moving the location of secondary air addition, from the radial ports in the transition section to the axial and deep staged ports in the boiler, was examined. The secondary air was distributed between radial and axial locations in one series of staging tests and between radial and deep staged ports (located 132 cm from the boiler front face) in a second series of tests. A water-cooled boom, aligned with the centerline of the boiler, was used to supply the deep stage air. Again, first-stage stoichiometry was optimized for each test condition.

During fuel staged NO control tests, the effect of diverting part of primary

fuel to staged locations in the burner and boiler was studied. The staged fuel was natural gas, with no ammonia dopant. The first-stage stoichiometry was optimized with respect to NO emission. In the case of fuel staging in the burner, the secondary natural gas was added, using a water-cooled boom, down the centerline of the boiler; secondary air was added axially into the boiler to allow sufficient fuel-rich zone residence time. In the case of fuel staging in the boiler, the secondary natural gas was added at an angle of 45 degrees, using water-cooled booms, from two ports in the boiler front face. Secondary air to complete primary fuel combustion was added radially into the transition section, while burnout air for secondary fuel combustion was added axially into the boiler, using six axial ports on the boiler front face.

BURNER BASELINE PERFORMANCE

The results of these tests are plotted in Fig. 2. The two dotted curves in the figure correspond to the long (two spool modules) and short (one spool module) configurations of the unmodified facility (see Fig. 1a). The solid curve corresponds to the facility configuration used in the rest of this study. The dotted curves show the effect of burner residence time on the stack NO levels. The curves indicate a strong sensitivity of stack NO to changes in first-stage stoichiometry. For the long burner configuration, with a residence time of 600 ms, the minimum stack NO concentration was about 60 ppm at a primary fuel nitrogen content of 0.66 percent. With the shortened burner configuration, with a residence time of 350 ms, the minimum NO stack concentration rose to about 200 ppm at the same fuel nitrogen content. The solid curve was obtained by burning a fuel with 5.8 percent fuel nitrogen (as ammonia) in the vertical burner. A minimum NO emission of 315 ppm occurred at a first-stage stoichiometry of about 0.78. Thus, additional combustion modifications are necessary to achieve the program goal of 175 ppm maximum NO emission.

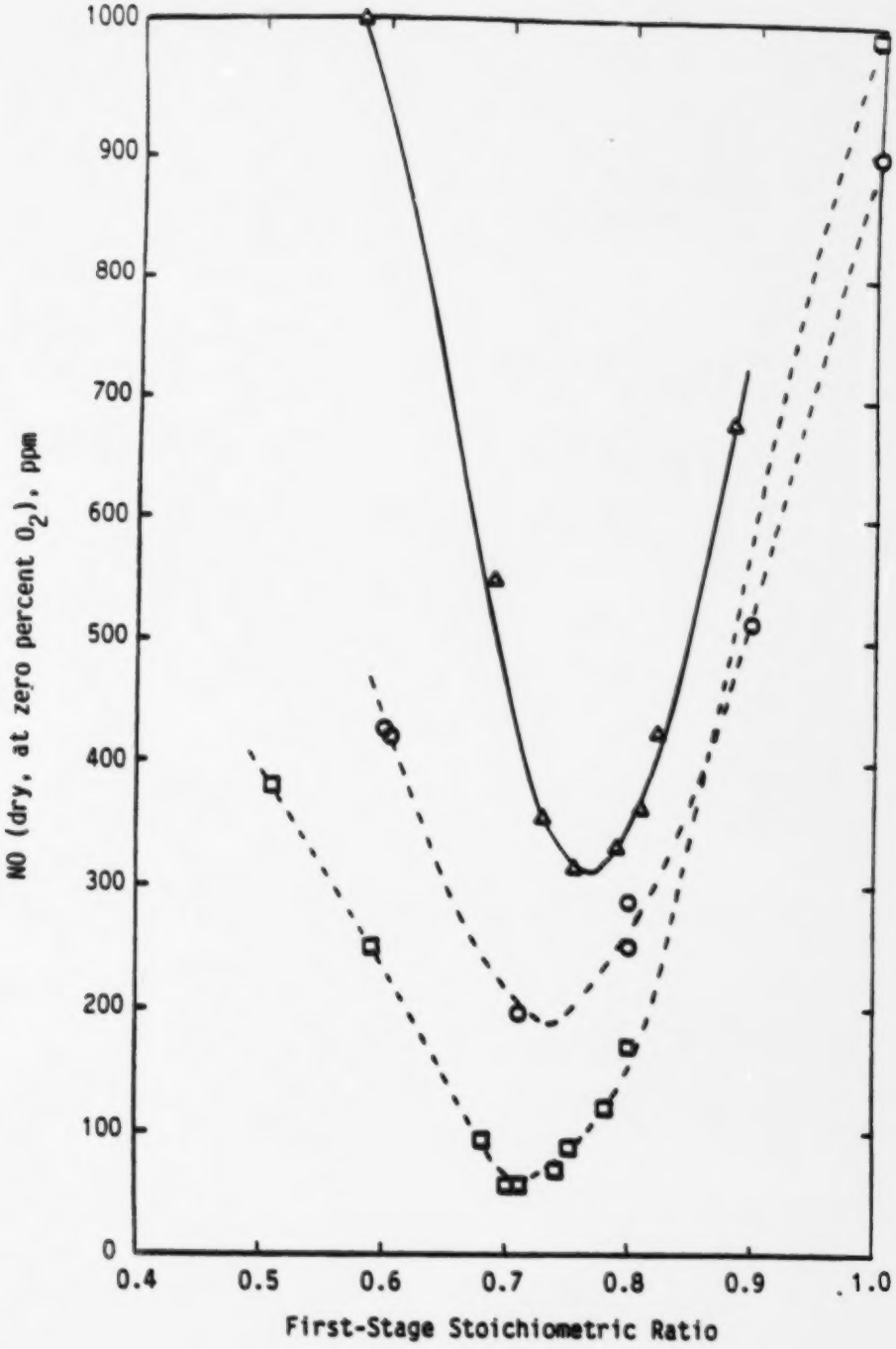


Figure 2. Effect of reduced burner size. The dotted lines represent results from the horizontal burner firing natural gas containing 0.66 percent nitrogen as ammonia. The square symbols correspond to long burner (600 ms) test results; the circles represent short horizontal burner (350 ms) test results. The solid line with triangle symbols shows results with the short, vertical burner firing natural gas containing 5.8 percent nitrogen as ammonia.

UNSTAGED NO CONTROLS

Excess Air Variation Results

The effect of excess air variation on stack NO is shown in Fig. 3. Decreasing excess air from 15 to 5 percent reduces the exhaust NO from 315 to 290 ppm. NO emissions increase only slightly beyond an exhaust stoichiometry of about 1.2. While reducing excess air does provide some NO reduction, maintaining an exhaust excess air level of 15 percent is important for achieving high combustion efficiency.

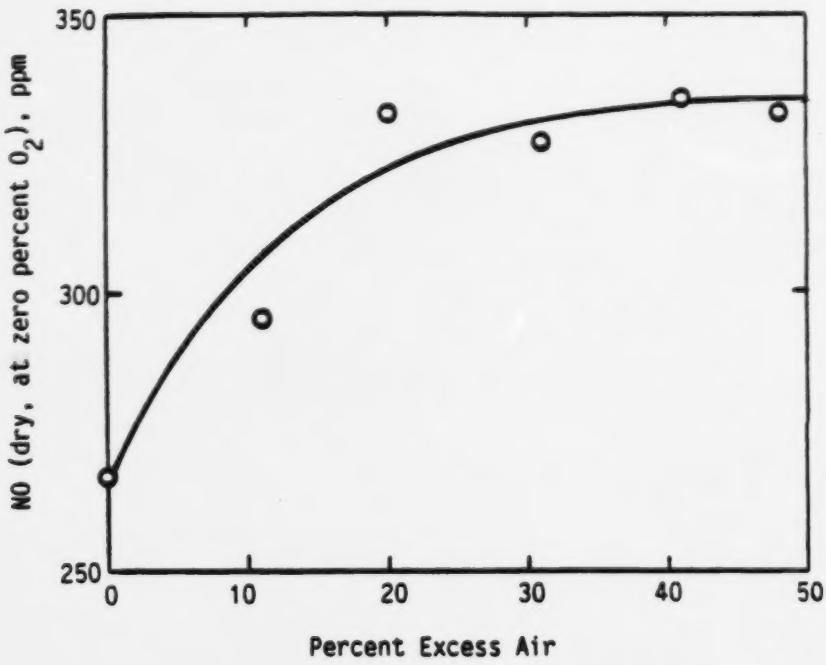


Figure 3. Excess air variation results.

Load Reduction Results

The effect of load reduction on stack NO is shown in Fig. 4. As load was decreased from a nominal condition of 0.6 MW to about 65 percent of nominal, the stack NO concentration dropped from 315 to 260 ppm. Load reduction corresponds to an increase in residence time and, thus, a decrease in NO emissions. Reducing load by 35 percent increases the residence time from 250 ms to about 410 ms. However, boiler steam requirements may make load reduction an impractical means of NO_x control.

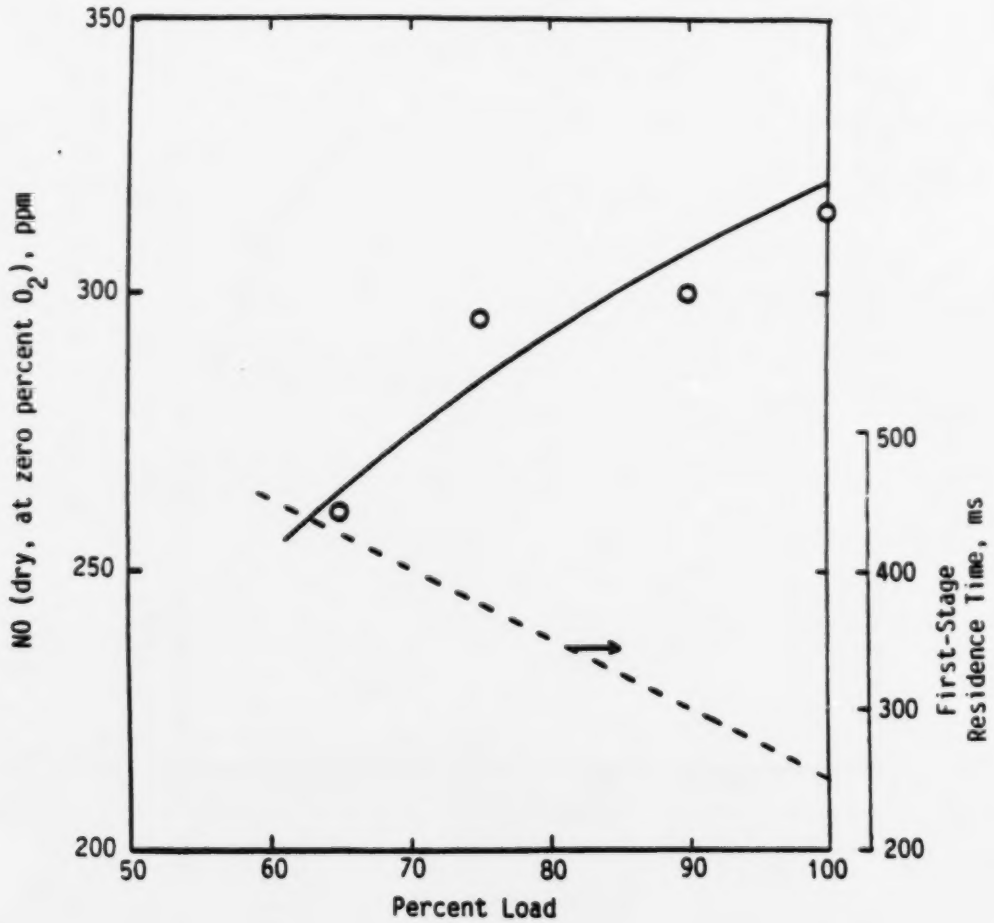


Figure 4. Load variation results.

Fuel/Waste Co-Firing Results

The effect of co-firing a nitrogen-free fuel (natural gas) and a surrogate nitrogenous waste (ammonia-doped natural gas) with 5.8 percent nitrogen is shown

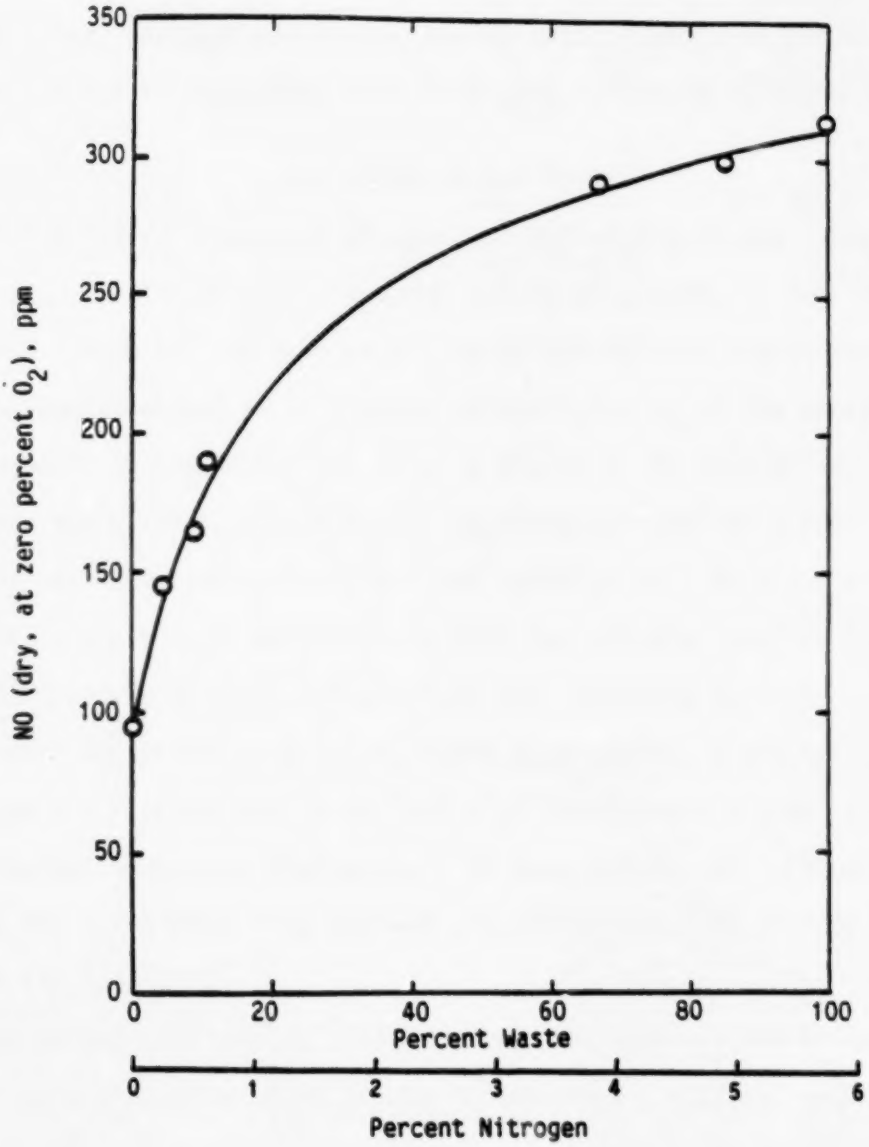


Figure 5. Fuel/waste nitrogen variation results.

in Fig. 5. Data are plotted for the full range of co-firing conditions, from 100 percent fuel to 100 percent surrogate waste. Exhaust NO level increases with increasing fuel nitrogen content in the fuel/waste stream, as expected. However, exhaust NO levels become less sensitive to fuel nitrogen contents above 3 percent, with emissions peaking at less than 350 ppm. It should be noted that, for conventional unstaged combustion, the NO emission would be expected to exceed 1000 ppm for firing a fuel with a nitrogen content of more than 5 percent.

AIR STAGED NO CONTROLS

Test results for two cases of secondary air staging in the boiler are shown in Fig. 6. The axial air staging results show a drop in minimum NO concentration from 315 ppm with no staging to 220 ppm with 100 percent of the secondary combustion air moved from the radial injectors to the axial injectors. The temperature of the combustion gases is higher in the transition section than in the boiler; also, the mixing of secondary air and combustion gas is more rapid when the secondary air is added radially into the transition section. Hence, more thermal NO is generated and more fuel nitrogen species fragments are oxidized with radial air addition into the transition section than with axial addition into the boiler. Similarly, lower temperatures in the boiler at the deep staged air location and longer fuel-rich zone residence time result in a lower NO emission when the secondary air is deep staged. With all of the secondary air being added from the deep staged location, the minimum NO level was about 160 ppm.

Based on the test results just described, the deep staging of secondary air is an effective means of minimizing NO emissions. However, such staging may lead to burnout problems, which is of great concern when co-firing waste. Extending the fuel-rich zone from the precombustion chamber into the boiler

exposes the reducing combustion gases to the cool boiler walls, which may result in slagging and/or sooting. Further, the lower combustion gas temperatures in the boiler slow the fuel-rich nitrogen kinetics.

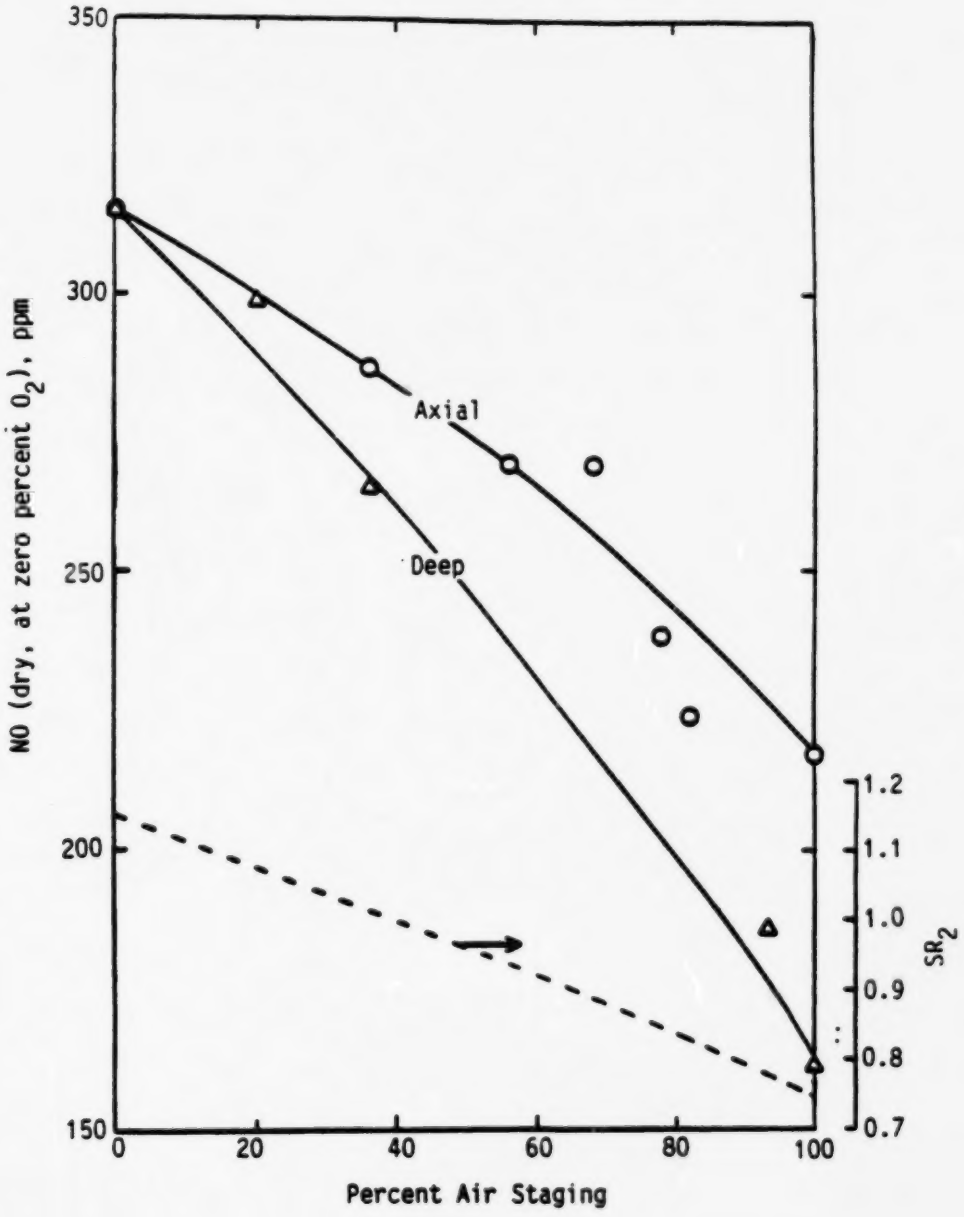


Figure 6. Air staging results.

FUEL STAGED NO CONTROLS

Burner Fuel Staging Results

Holding total load constant, fuel was diverted from the primary fuel injector to a secondary injector near the precombustion chamber exit (see Fig. 1b), thus creating two stoichiometric zones in the burner in addition to the burnout zone in the boiler. The staged fuel, undoped natural gas, provides a burst of hydrocarbon radicals that accelerate the reduction of primary fuel nitrogen to N_2 prior to secondary air injection. Secondary air was injected through the axial injectors. The results, plotted in Fig. 7, show a decrease in NO emission with increasing fuel staging. Two effects contribute to this decrease in NO emissions with fuel staging: (1) fuel nitrogen reduction mechanisms are accelerated due to increased radical concentrations, and (2) combustion gases

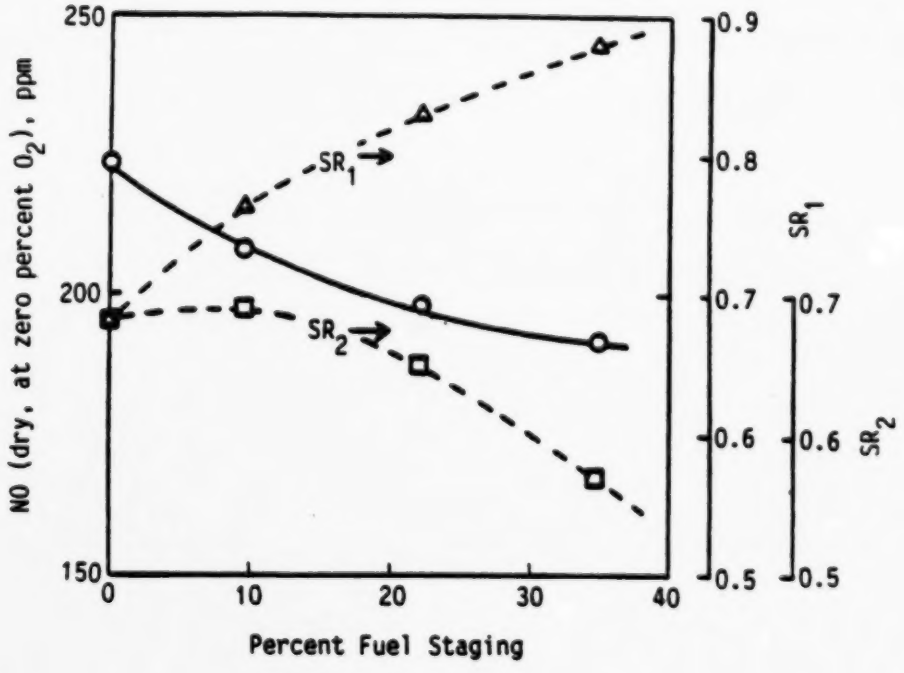


Figure 7. Burner fuel staging results.

from the high nitrogen content primary fuel are diluted by the combustion gases from the nitrogen-free secondary fuel. With 35 percent of the fuel staged, the exhaust NO levels decreased to 190 ppm, from 220 ppm at zero percent staging (and axial secondary air addition). The figure also shows that the optimum first-stage burner stoichiometry (SR_1) increases with increasing fuel staging, while the optimum second-stage burner stoichiometry (SR_2) decreases slightly. This result is consistent with kinetic model predictions of optimum stoichiometries for the two burner stages. A first-stage stoichiometry of 90 percent theoretical air should result in a higher destruction efficiency of the primary fuel/waste stream than with a more fuel-rich first stage.

Boiler Fuel Staging Results

As in the tests just described, total boiler load was held constant while fuel was diverted from the primary fuel injector to a secondary injector. In this case, the staged fuel (undoped natural gas) was injected into the boiler downstream of the secondary radial air addition. Thus, a four-stage combustion process is established, consisting of a fuel-rich burner zone and three boiler zones characteristic of reburning (i.e, fuel-lean, fuel-rich, fuel-lean). As already described, all of the staged air and fuel flows were injected from the front face of the boiler at various angles, resulting in the three boiler stoichiometric zones. Figure 8 shows that the NO emissions decrease with an increase in fuel staging. This is due to both primary NO destruction and primary combustion gas dilution. Two second-stage stoichiometries (SR_2) were established: 1.1 and 1.0. With 35 percent fuel staging, the exhaust NO levels were reduced to 195 ppm (from 315 ppm) at a SR_2 of 1.1 and to about 160 ppm at a SR_2 of 1.0. Due to less distinct stoichiometric zones than typically established in reburning application and incomplete nitrogen chemistry in the primary flame, the NO reduction by fuel staging is not quite as great as that obtained

when the staged fuel is injected farther downstream of the fuel-lean primary combustion zone [12]. However, the configuration used in these tests requires no boiler penetrations. With this multistaged combustion, the NO emission goal of

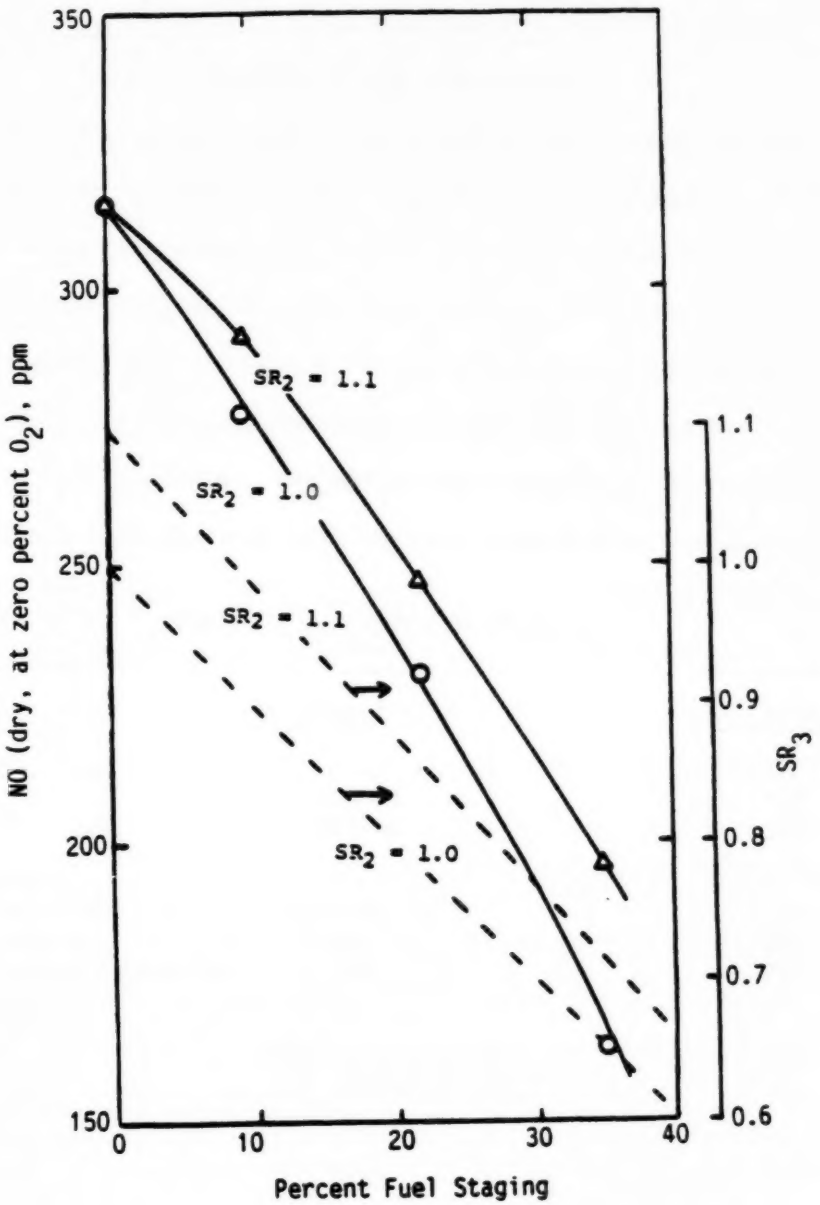


Figure 8. Boiler fuel staging results.

175 ppm is met. In addition, the complete destruction of the primary fuel/waste stream appears to be ensured by providing all of the required primary combustion air prior to entry into the boiler, and then passing the primary combustion gases through a secondary flame.

DISCUSSION AND CONCLUSIONS

Results from the various combustion modification schemes for the reduction of NO are summarized in Table 1. Note that these results were obtained at optimal first-stage stoichiometries. From the table it can be seen that deep air staging and fuel staging in the boiler are most effective in minimizing NO emissions. However, deep air staging not only presents problems of hardware modification due to boiler penetrations, but may also lead to inefficient combustion. On the other hand, the boiler fuel staging hardware modifications used in this study were designed with retrofit feasibility and efficient com-

TABLE 1. SUMMARY OF RESULTS

Scheme	Amount	NO_x (ppm)
Burner Baseline		
-Long	600 ms	90
-Short	250 ms	315
Unstaged Control		
-Excess Air Reduction	to 105% TA*	290
-Load Reduction	35%	260
-Fuel Nitrogen Reduction	35%	295
Air Staged Control		
-Axial	all secondary air	220
-Deep	all secondary air	160
Fuel Staged Control		
-Burner	35%	190
-Boiler		
$-SR_2=1.1$	35%	195
$-SR_2=1.0$	35%	160

*TA = Theoretical Air

bustion in mind. In the tests described here, all of the secondary combustion air necessary for primary fuel burnout is introduced with rapid mixing at high temperatures in the water-cooled transition section between the burner and boiler. Further, the staged fuel and air from the front face of the boiler provide a secondary flame for increased primary fuel/waste destruction, similar to incinerator afterburners.

Some mention must be made of the limitations of these results. First, little information has been collected to date on surrogate fuel/waste burnout. Burning natural gas and ammonia mixtures, rather than the liquid fuel/waste mixtures and pulverized coals that are encountered in practice, allows for well-controlled parametric testing for NO_x emission evaluation, but it does not provide for good burnout simulation. Stack emissions of CO were less than 10 ppm for every test condition reported here. However, in-furnace sampling would provide more insight into the potential for fuel burnout problems. Another problem involved in testing with natural gas is the simplified mixing processes and faster kinetics characteristic of gaseous fuel combustion. NO emissions from the shortened precombustion chamber burner would be lower for natural gas firing than for the firing of fuels and wastes that require vaporization or pyrolysis. Fuel oil tests are needed to confirm the NO emission measurements and fuel burnout speculations reported here.

Another limitation of this study is that the results are applicable only in the range of temperatures characteristic of the firetube package boiler. Temperatures in the package boiler simulator range from 1700 K at the boiler entry to 1250 K at the boiler exit. To avoid high thermal NO formation in the primary combustion gas burnout, sufficient heat must be extracted in the transition section to lower the combustion gas temperatures to less than 1800 K.

Finally, note that the low NO emissions from the fuel staging tests are

achieved largely by the dilution of the primary combustion gases with secondary flame gases, which do not have a fuel nitrogen input. Actual molar destruction of NO is small in these tests. However, this dilution is coupled with the NO formation and destruction processes and should not be discounted. From the standpoint of NO minimization and fuel/waste destruction maximization, the overall emissions per unit mass of input should be considered. From this perspective, fuel staging in combination with the shortened precombustion chamber burner appears to be the most attractive combustion modification for high nitrogen content fuel/waste firing in boilers.

Further characterization of this multistaged burner design is ongoing at EPA. Fuel burnout is being measured to optimize both combustion efficiency and NO emission. Pyridine and fuel oil mixtures are being used for this study.

ACKNOWLEDGMENT

This work was funded by EPA's Air and Energy Engineering Research Laboratory at Research Triangle Park, North Carolina. The authors wish to express their appreciation for the support provided by Charles Pendergraph and Darryl Williams of Acurex Corporation.

REFERENCES

1. Cleland, J.G., and Kingsbury, G.L., "Multimedia Environmental Goals for Environmental Assessment: Volumes I and II," EPA-600/7-77-136a,b (NTIS PB276919, 276920), November 1977.

2. Kingsbury, G.L., et al., "Multimedia Environmental Goals for Environmental Assessment: Volumes III and IV," EPA-600/7-79-176a,b (NTIS PB80-115108, -115116), August 1979.

3. Keinhorst, H., "Legal Instruments and the State of Technology for Reducing NO_x Emissions in the Federal Republic of Germany," In: Proceedings: 1985 Symposium on Stationary Combustion NO_x Control, Volume 1: Utility Boiler Applications, EPA-600/9-86-021a (NTIS PB86-225042), July 1986, p. 4-1.

4. Lanier, W.S., and Robinson, S.B., "EPA Workshop on N_2O Emission from Combustion," EPA-600/8-86-035 (NTIS PB87-113742), September 1986.

5. Gerber, C.R., Opening Remarks, In: Proceedings: 1985 Symposium on Stationary Combustion NO_x Control, Volume 1, EPA-600/9-86-021a (PB86-225042), July 1986, p. 2-1.

6. "Standards of Performance for New Stationary Sources - Volume 1: Summary and Standards," EPA-340/1-82-005a, June 1982.

7. Waterland, L.R., et al., "Environmental Assessment of Stationary Source NO_x Control Technologies," EPA-600/7-82-034 (NTIS PB82-249350), May 1982.

8. England, G.C., et al., "Evaluation and Demonstration of Low-NO_x Burner Systems for TEOR Steam Generators - Design Phase Report," EPA-600/7-84-076 (NTIS PB84-224393), July 1984.

9. England, G.C., et al., "Evaluation and Demonstration of Low-NO_x Burner Systems for TEOR Steam Generators: Final Report - Field Evaluation of Commercial Prototype Burner," EPA-600/7-85-013 (NTIS PB85-185874), March 1985.

10. Castaldini, C., et al., "Environmental Assessment of an Enhanced Oil Recovery Steam Generator Equipped with an EPA Heavy Oil Low-NO_x Burner: Volumes I and II," EPA-600/7-86-013a,b (NTIS PB86-191475,-191483), April 1986.

11. Wendt, J.O.L., Sternling, C.V., and Matovich, M.A., "Reduction of Sulfur Trioxide and Nitrogen Oxides by Secondary Fuel Injection," Fourteenth Symposium (International) on Combustion, The Combustion Institute, 1973, p. 897.

12. Takahashi, Y., et al., "Development of Mitsubishi 'MACT' In-Furnace NO_x Removal Process." Presented at the U.S.-Japan NO_x Information Exchange, Tokyo, Japan, May 25-30, 1981. Published in Mitsubishi Heavy Industries, Ltd: Technical Review, Vol. 18, No. 2.

13. Mulholland, J.A., and Lanier, W.S., "Application of Reburning for NO_x Control to a Firetube Package Boiler," Journal of Engineering for Gas Turbines and Power, Vol. 107, No. 3, ASME, July 1985, p. 739.

14. Mulholland, J.A., and Hall, R.E., "The Effect of Fuel Nitrogen in Reburning Application to a Firetube Package Boiler," In: Proceedings: 1985 Symposium on Stationary Combustion NO_x Control, Vol. 1, EPA-600/9-86-021a (NTIS PB86-225042), July 1986, p. 22-1.

15. Mulholland, J.A., and Hall, R.E., "Fuel Oil Reburning Application for NO_x Control to Firetube Package Boilers." Presented at the Joint ASME/IEEE Power Generation Conference, 85-JPGC-APC-6, Milwaukee, Wisconsin, October 1985. To be published in ASME Transactions Journal.

16. Lanier, W.S., Mulholland, J.A., and Beard, J.T., "Reburning Thermal and Chemical Processes in a Two-Dimensional Pilot-Scale System," Twenty-first Symposium (International) on Combustion, The Combustion Institute, 1986 (in press).

5. Gerber, C.R., Opening Remarks, In: Proceedings: 1985 Symposium on Stationary Combustion NO_x Control, Volume 1, EPA-600/9-86-021a (PB86-225042), July 1986, p. 2-1.

6. "Standards of Performance for New Stationary Sources - Volume 1: Summary and Standards," EPA-340/1-82-005a, June 1982.

7. Waterland, L.R., et al., "Environmental Assessment of Stationary Source NO_x Control Technologies," EPA-600/7-82-034 (NTIS PB82-249350), May 1982.

8. England, G.C., et al., "Evaluation and Demonstration of Low-NO_x Burner Systems for TEOR Steam Generators - Design Phase Report," EPA-600/7-84-076 (NTIS PB84-224393), July 1984.

9. England, G.C., et al., "Evaluation and Demonstration of Low-NO_x Burner Systems for TEOR Steam Generators: Final Report - Field Evaluation of Commercial Prototype Burner," EPA-600/7-85-013 (NTIS PB85-185874), March 1985.

10. Castaldini, C., et al., "Environmental Assessment of an Enhanced Oil Recovery Steam Generator Equipped with an EPA Heavy Oil Low-NO_x Burner: Volumes I and II," EPA-600/7-86-013a,b (NTIS PB86-191475,-191483), April 1986.

11. Wendt, J.O.L., Sternling, C.V., and Matovich, M.A., "Reduction of Sulfur Trioxide and Nitrogen Oxides by Secondary Fuel Injection," Fourteenth Symposium (International) on Combustion, The Combustion Institute, 1973, p. 897.

12. Takahashi, Y., et al., "Development of Mitsubishi 'MACT' In-Furnace NO_x Removal Process." Presented at the U.S.-Japan NO_x Information Exchange, Tokyo, Japan, May 25-30, 1981. Published in Mitsubishi Heavy Industries, Ltd: Technical Review, Vol. 18, No. 2.

13. Mulholland, J.A., and Lanier, W.S., "Application of Reburning for NO_x Control to a Firetube Package Boiler," Journal of Engineering for Gas Turbines and Power, Vol. 107, No. 3, ASME, July 1985, p. 739.

14. Mulholland, J.A., and Hall, R.E., "The Effect of Fuel Nitrogen in Reburning Application to a Firetube Package Boiler," In: Proceedings: 1985 Symposium on Stationary Combustion NO_x Control, Vol. 1, EPA-600/9-86-021a (NTIS PB86-225042), July 1986, p. 22-1.

15. Mulholland, J.A., and Hall, R.E., "Fuel Oil Reburning Application for NO_x Control to Firetube Package Boilers." Presented at the Joint ASME/IEEE Power Generation Conference, 85-JPGC-APC-6, Milwaukee, Wisconsin, October 1985. To be published in ASME Transactions Journal.

16. Lanier, W.S., Mulholland, J.A., and Beard, J.T., "Reburning Thermal and Chemical Processes in a Two-Dimensional Pilot-Scale System," Twenty-first Symposium (International) on Combustion, The Combustion Institute, 1986 (in press).